ANL/APS/TB-53

Insertion Devices:
Magnetic Measurements and Tuning

I. Vasserman, E. Gluskin, J. Xu

October 2010

Part 1 – Magnetic Sensors and Measurement Techniques

Insertion devices (IDs) are the primary source of x-ray radiation for APS beamlines. The APS storage ring and IDs should meet stringent requirements of delivering uninterrupted high-quality x-ray beam with specified brightness and level of spatial stability [1]. For IDs, these requirements are directly translated to the quality of their magnetic and mechanical performance. In order to meet, maintain and verify the ID's magnetic performance, the Magnetic Measurement Facility (MMF) has been developed [2]. It is constantly being improved and its equipment upgraded. As of now, the MMF consists of two measurement benches, 3 meters and 6 meters long. Each bench is equipped with a set of interchangeable magnetic sensors. Mechanical systems installed on both benches provide for highly accurate motion of the magnetic sensors, three linear and one angular. The control system synchronizes the readings of the sensor's signal with the encoder readings during the process of continuous sensor motion. A data acquisition system collects and processes measurement data, and a graphic user interface presents it on the computer screen as plots and tables. These systems have been partially described in technical reports and conference presentations [3].

Another important part of a MMF is the calibration system [4]. This system consists of the calibration electromagnet and a set of Nuclear Magnetic Resonance (NMR) probes. The calibration magnet serves for calibration of Hall probes.

There is another magnetic measurement system based on a set of Helmholtz coils. This system is used to measure magnetic moments of individual permanent magnets [5].

ID Magnetic Specifications

An electron beam passing through a periodic magnetic device–an ID–generates quasi-monochromatic radiation. Radiation properties, such as the radiation brightness at specific wavelengths–harmonics, angular distributions, polarization, etc.–depend on characteristics of the ID's magnetic field and electron beam parameters. At the same time, as a magnetic device, the ID will affect the electron beam trajectory and other characteristics.

An undulator, as an x-ray source at the APS, should meet the following specified requirements: brightness of the radiation at the first and third harmonics should be at least 95% and 75%, respectively, of that calculated from a theoretically ideal undulator. At the same time, as a part of the APS storage ring magnetic lattice, each ID should meet stringent requirements of the magnetic field quality in order to minimize the effects of perturbation on the closed orbit, increasing of the beam emittance, and decreasing of the beam lifetime and the dynamic aperture for the entire gap range of the ID. The total budget of such perturbations translates into specific measured parameters of the ID magnetic field (see Table 1 for the first and second field integrals and Table 2 for multipole components).

Table 1. Field integral specifications

	Horizontal field	**Vertical field**
First field integral	50 Gauss-cm	100 Gauss-cm
Second field integral	100 kGauss-cm^2	100 kGauss-cm^2

Additional requirements are set for the first and second field integrals (Table 2)

Table 2. Specifications of the field integral multipole components for APS IDs

Multipole n	**Normal component (b_n)**	**Skew component (a_n)**
1 Quadrupole	50 Gauss	50 Gauss
2 Sextupole	200 Gauss/cm	100 Gauss/cm
3 Octupole	300 Gauss/cm^2	50 Gauss/cm^2

A somewhat different set of requirements should be met by IDs used for free-electron lasers (FELs). One of the most important requirements in that case is the straightness of the beam trajectory inside the device. The set of specifications for IDs built for the Linac Coherent Light Source (LCLS) FEL are shown in the Table 3.

Table 3. Tolerances for the LCLS undulator segment.

Parameter	**Specified Value**
Trajectory excursion (both planes)	2 μm
Radiation amplitude deviation	2%
Phase slippage between undulators	10°
Vertical positioning error (B_y)	50 μm
Vertical positioning error (B_x)	10 μm

The purpose of magnetic measurements and tuning is to meet the set of requirements from Tables 1-3 for each APS ID or LCLS ID.

ID Magnetic Measurement System

The APS ID magnetic measurement system consists of two separate instruments. Each of these instruments includes a precise granite bench (one is 6 m and another 3 m long), a set of interchangeable magnetic sensors, mechanical systems to position and move the magnetic sensors, and a control and data acquisition system. All systems are identical except for the length of motion along the benches.

Mechanical systems for both benches were upgraded in 2010. They are able to provide synchronization within 30 ns motion/positioning of magnetic sensors with 0.005° angular and 0.5μ linear resolution while acquiring voltage signals from coil-type sensors with 16-bit resolution and Hall probe signals with 23-bit resolution. Each magnetic measurement bench is equipped with a set of support systems for the magnetic sensors (Fig. 1).

Fig. 1. General view of the 6-m bench with the Hall probe carriage and long-coil stages.

All support systems provide 4-dimensional controlled linear and rotational motions and can accommodate different types of magnetic sensors, sometimes interchangeably.

The control and data acquisition systems are identical for both instruments [6, 7] and preserve the same configuration for all different types of measurements with just one exception that will be mentioned below. Layouts of the control and data acquisition system are shown in Figs. 2 and 3.

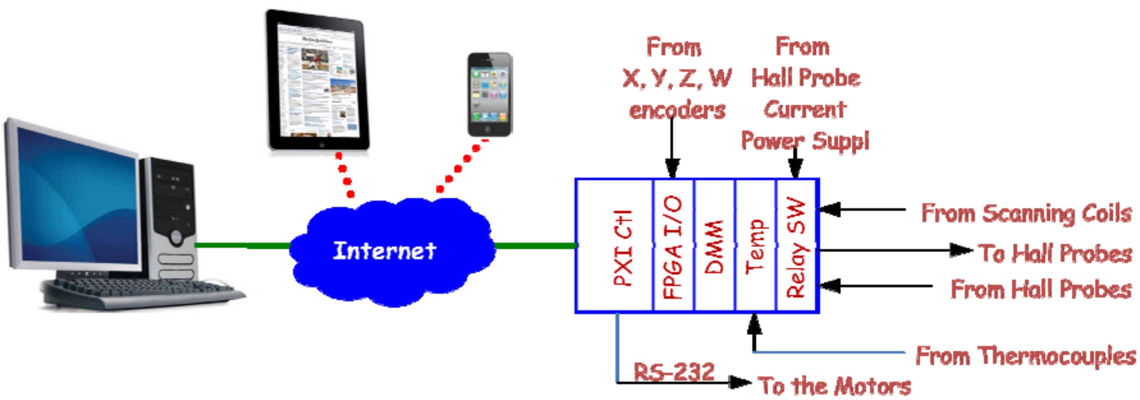

Fig. 2. Schematic of the control and data acquisition system for the Hall probe and moving coil measurements.

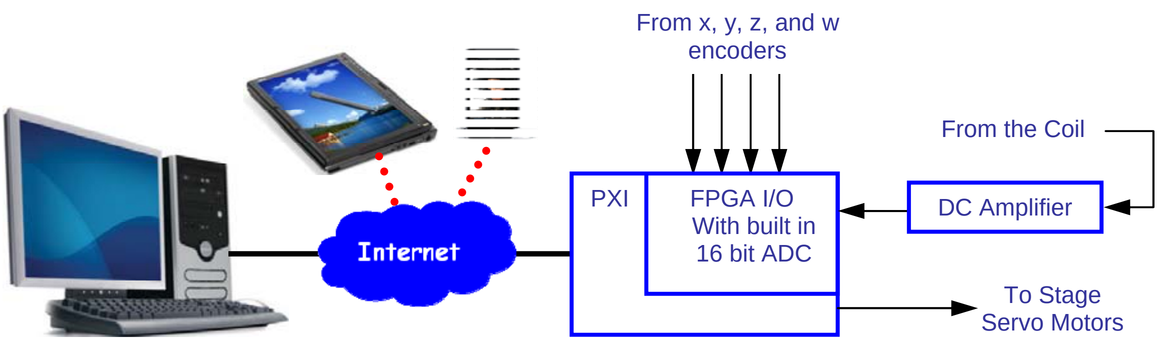

Fig. 3. Schematic of the control and data acquisition system for long-coil measurements.

Magnetic measurement systems with different sensors have been used extensively for several decades to characterize different types of accelerator electromagnetic or permanent-magnet components, such as dipoles, quadrupoles, pulsed magnets, etc. The majority of these components, including magnets for non-accelerator applications, have at least one common feature: an integrated field for each of them is significantly higher (sometimes many orders of magnitudes) compared with the integrated field of the Earth's magnetic field for the same length of the integration.

Insertion devices represent quite a different class of magnets. Due to their periodic, sign-alternating magnetic field structure, the field integrals of IDs are comparable to or, in many cases, much smaller than those of the Earth's magnetic field. As a result, although types of magnetic sensors used to measure IDs are the same as for other magnets, the mechanical design, electronics and data processing for ID magnetic sensors are quite specific.

A list of the magnetic sensors used at the APS ID measurements systems is shown in Table 4.

Table 4. Magnetic sensors for ID measurements.

Sensor	**Measured values**
Hall probe	Magnetic field map in X* and Y*, field integrals
Stretched rotating rectangular loop/coil	First and second field integrals in X and Y, multipole components
Stretched wire	First and second field integrals in X, multipole components
Short[1] moving coil	First and second field integrals in X and Y, average trajectories
Moving minicoil[2]	Magnetic field map, field integrals

*X- transverse to the beam direction horizontal coordinate, Y-transverse to the beam direction vertical coordinate.
[1]- Short coils are much smaller than the stretched rotating coil and are comparable with the period of ID, which is typically equal to several cm.
[2]- Minicoil is just a few millimeters wide, i.e., about ten times smaller than the LCLS ID or Undultor A period.

Hall Probe System

A Hall probe is the most common element of any magnet measurement system. But the specific magnetic configuration of IDs, such as a sign-changing periodic field with relatively high gradients, and an ID's magnetic specification require specialized Hall probes. The APS has being testing and operating several types of Hall probes by measuring and tuning IDs at the MMF. A short summary of this experience accumulated in the last fifteen years is presented below.

A Hall probe for ID measurements consists of the Hall probe sensor, the sensor's holder, called the magnetic probe module, that could also contain a temperature control device, and an electronic module that, for the Sentron Hall probe, is called the transducer [8, p.309]. The holder is installed on stages that provide precisely controlled linear and angular motions in all required directions (Fig. 4).

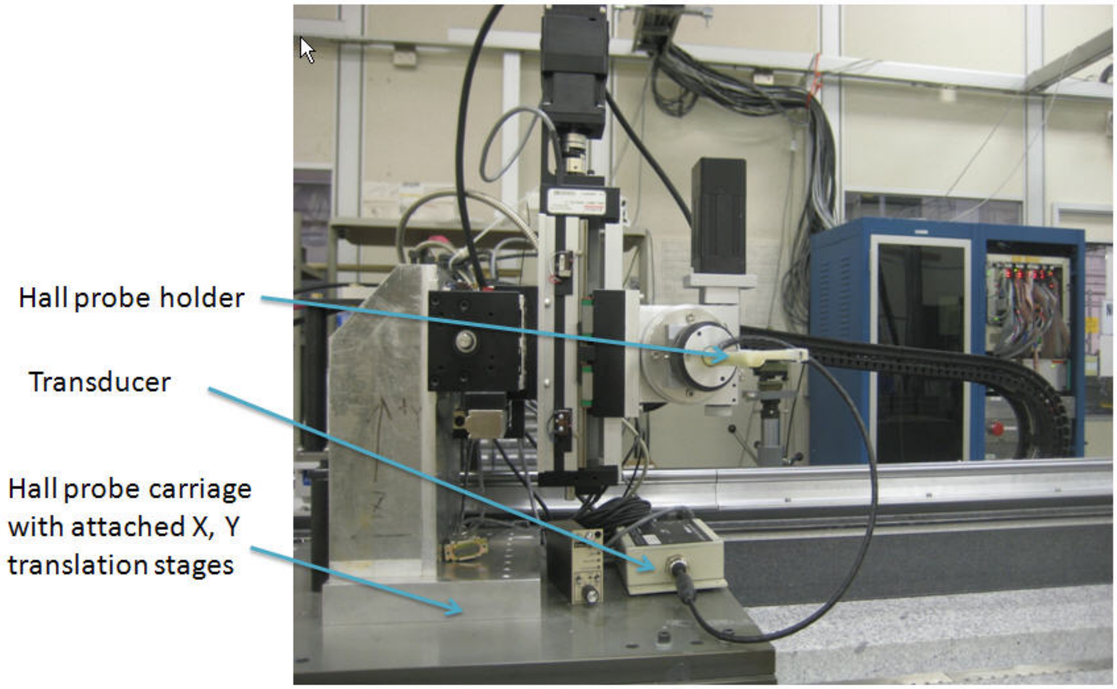

Fig. 4 Hall probe system at the 6-m bench.

The input of the electronic module is connected to the holder, and the output is connected to the readout electronics. All these elements together constitute the ID measurement Hall probe system.

The Hall probe system should provide stable, reproducible and efficient measurements of IDs. The quantitative requirements for the Hall probe system performance, and any other magnetic sensor, are derived from the ID's specifications [1], and are also the product of generally accepted good experimental practices.

Below several of these requirements for the Hall probe system and its components are described in some detail and then summarized in Table 5.

As already mentioned, IDs generate a periodical, sign-changing magnetic field. Periodicity along the Z direction could vary between 10 to 100 mm. Therefore in order to minimize the integration of the signal during the measurements involved in translation along the Z direction, the dimension of the Hall probe sensor should be significantly smaller than an ID period. In the Y direction, the ID gap defines the limit, which could be as small as 5 mm. And therefore the dimensions of Hall probe sensors used at the APS MMF are typically a small fraction of a millimeter in any direction. Although the holder could be significantly larger, up to several mm in the X and Y directions, it has to fit with an adequate margin into the smallest ID gap.

Since Hall probe sensors are very small, it is possible and quite desirable to have two, for each field component, independent sensors packaged in the same holder. That improves the efficiency of measurements and is advantageous for the probe alignment process. One of the most commonly used Hall probes at the APS–a two-axis Sentron transducer–has two sensors in the same holder placed in a very close proximity to each other.

Insertion devices, even planar ones, always generate crossed magnetic fields in the X-Y plane, mostly with highly unequal components, strong in the Y and weak in the X direction. In order to achieve and maintain reliable measurements of a weak horizontal field, it is very important to have a sensor equipped with compensation of the planar Hall effect (PHE), i.e., to have a system that minimizes the influence of the high-field component on the measurement of the low-field component [8]. Although the two-axis Sentron transducer has such compensation built-in, it is still quite sensitive, down to the level of several microns, to the vertical positioning in the case of the measurements of the horizontal field integrals in the presence of a relatively strong (>1T) vertical field [9]. The problem of compensation of the PHE and making it independent from very accurate vertical positioning has been addressed recently by implementing a special mode of operation of the one-axis Arepoc Hall probe [10].

For routine characterization and tuning of APS IDs, typical requirements for accurate Hall probe positioning can be derived from values of required radiation brightness, the ID's period, and field integrals. This would lead to approximately a 20-30 micron level of accuracy in the Z and Y directions. In the X direction, the sensitivity is quite low and the accuracy could also be much lower as well (usually ~0.5 mm).

But for several specific cases, such as the LCLS ID for example, when the straightness of the trajectory in both the X and Y directions should stay within 2 μm, an accurate, about 5-10 μm, vertical positioning of the Sentron Hall probe is required while mapping the horizontal field of the device. Also, the accuracy in positioning along the Z direction has to be within 10 μm in order to reliably track the phase-error fluctuations.

As mentioned above, currently the APS MMF mechanical and electronic systems are capable of positioning the Hall probe with an accuracy of 0.5 μm along the Z direction and 2 μm along the other axes. Although such accuracy is not required for a majority of APS IDs, it is quite useful to have the extra capability for future devices with smaller periods and more demanding requirements for straightness of the trajectory.

Some Hall probes can be quite sensitive to angular positioning, and angular alignment typically is a time-consuming process. Also, for such probes, one should be careful of preserving the same angular position for the ID measurements and during the probe calibration process. But as far as the mechanical system is concerned, angular alignment is not as challenging as accurate positioning. Typically it doesn't require better than 0.1° accuracy, which can be easily attained. The two-axis Sentron probe has an advantageous relatively low sensitivity to angular positioning.

As with any measuring device, noise characteristics are important parameters of the Hall probe performance. There are at least three sources of errors incurred with Hall probe measurements. One is the temperature dependence of the signal generated by the sensor, the second is the noise of the sensor itself and electronic components connected to the sensor, and the third is zero drift of these components. Statistical noise associated with the electronic white noise typically doesn't affect the field mapping much because many thousands of measurements are averaged within one scan. Also, the new types of Hall probes currently in use have relatively low thermosensitivity and the MMF is equipped with a temperature control system. Special steps though are taken to correct the systematic error associated with zero drift. This procedure is described in the next section.

As mentioned above, the two-axis Sentron probe is the most commonly used Hall probe at the APS MMF. But there are several other probes that can be quite useful and are sometimes necessary for special applications. One of them is the one-axis Hall probe from Arepoc. This probe can be used to measure the horizontal field in the presence of a very strong vertical field, and at the same time, avoids sensitivity in the vertical positioning, which is the downside of the two-axis Sentron probe. The measurement process consists of two consecutive scans. During the first scan, the standard wiring diagram of powering and readout of the probe is used. For the second scan, this diagram is reversed: signal output wires are connected to the powering device, and power wires – to the readout electronics. This process is illustrated in Fig. 5.

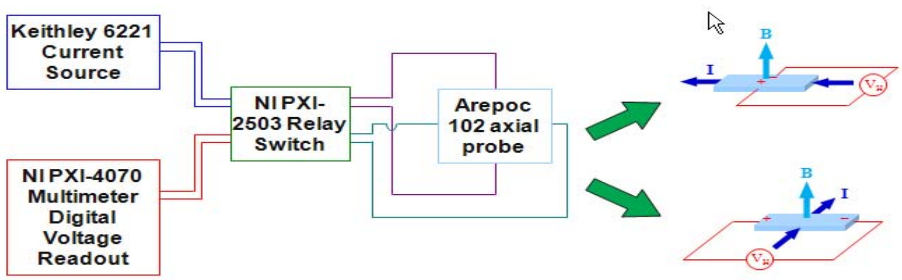

Fig. 5. Schematic of PHE-free horizontal field measurements with the axial Arepoc Hall probe.

Since, during the second scan, the sign of the signal resulting from the PHE has the opposite sign compared with the first scan, the averaging of these two measurements leads to almost perfect cancellation of the PHE [10].

Another Arepoc Hall probe was custom designed to conduct measurements of superconducting devices at low temperature. This particular probe is the two-axis device, and its round-shaped holder has a 4-mm diameter.

Table 5. Performance parameters of several Hall probe systems.

Hall probe system	**Sentron 2-axis**	**Arepoc 2-axis**	**Arepoc Axial PHE free**	**Group 3**
Sensitivity (V/T)	5	0.1	0.1	Digital
Area of application	ID measurements	SC device	Horizontal field measurements	calibration system
Travel speed (mm/sec)	150	150	150	Step by step
Electronics	Transducer	none	none	DTM-141

rms noise level (G)	<0.05	<0.5	<0.5	<0.5
Temperature stability (per 1°C)	$<10^{-4}$	$<10^{-4}$	$<2*10^{-4}$	10^{-5}
Nonlinearity %	<0.1	<1	<1	<0.1
Sensitivity to cross field	Low, sensitive to Y	High, sensitive to angle around X-axis	Low, not sensitive to positioning errors	N/A
Sensitive area Dimensions (mm)	0.25X0.25	0.05X0.05	0.05X0.05	4X1.6

Magnetic Measurements with Hall Probes

Standard steps for the preparation for magnetic measurements with the Hall probe include the alignment of the probe in the magnetic field of the ID and establishing the reference readings (zero offsets) of the magnetic field at the initial and final points of the scan. These points are typically located 300 mm away from each side of the ID magnetic structure in order to eliminate the gap dependence of the fringe field. Although, for the special case when two IDs may be placed on the same straight section and the IDs are separated only by ~60 mm, μ-metal shields are installed between them to eliminate the interdependence of fringe fields and field integrals for both IDs. For this special configuration, the location of the initial and final points of the scan is not critical due to shunting of the fringe field. It could remain the same as for a single ID or be moved closer to the device.

The first step of the preparation for measurements is the angular alignment. It is important to align the probe in the same angular position as it was during the probe calibration procedure. For a one-axis probe, the standard for angular alignment is to maximize the output signal in the homogeneous field. For the angular alignment of a two-axis probe in a planar ID, the signal from the axial (horizontal field) sensor has to be brought as close to zero as possible.

The second step is the alignment of the vertical position of the holder, which is done by scanning the holder along the Y axis and selecting the point of minimum signal of the vertical field sensor. An example of such a scan is shown in Fig. 6.

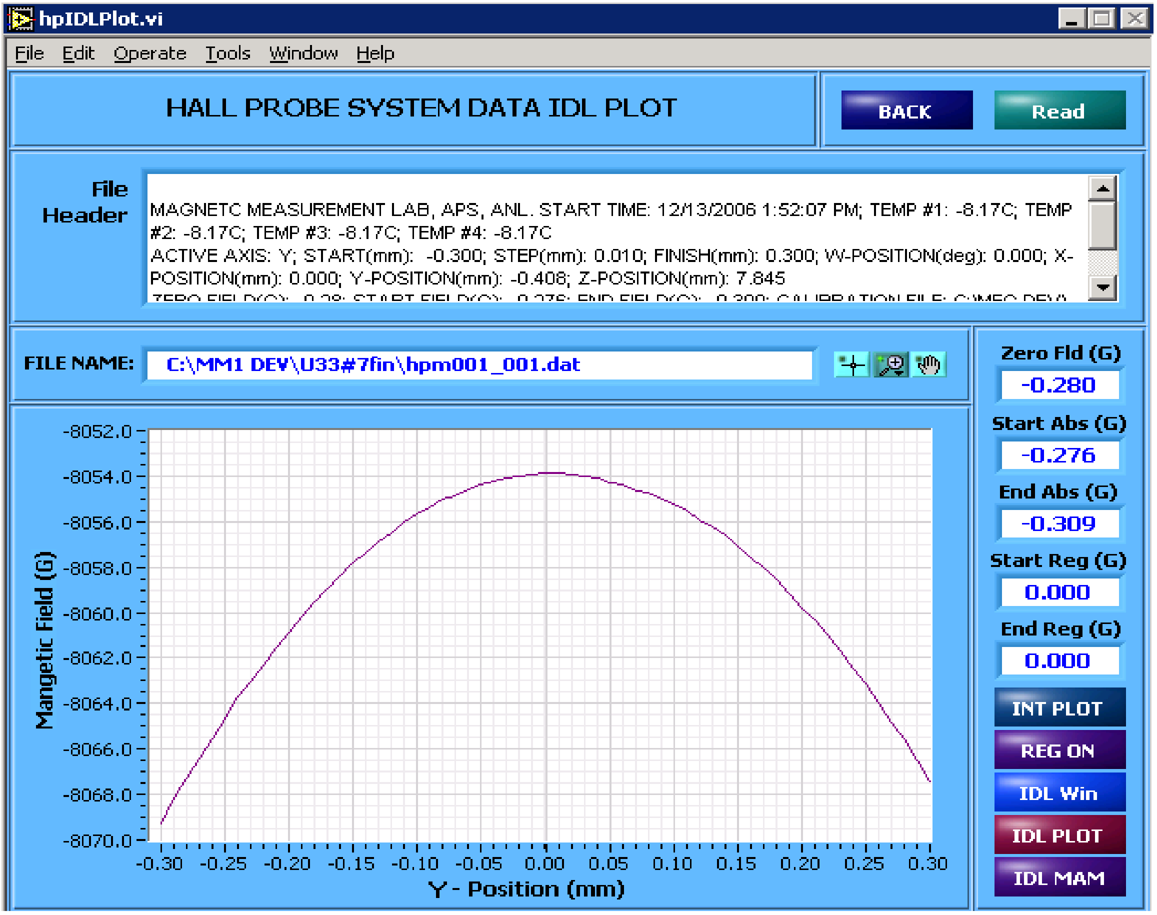

Fig. 6 Scan in Y after alignment is done to confirm that alignment is correct. (| $B_y(y=0)$ | has its minimum).

The third step in the preparation process consists of two reference measurements on both sides of the ID. Two measurements of the magnetic field are taken at the start and finish points of the scan after zeroing the offset with the holder surrounded by the μ-metal zero-field chamber. These reference measurements will permit one to offset the zero drift of the Hall probe and ensure reliable field integral measurements.

Usually conducting reference measurements once per each device after the ID is installed at the bench is enough. After measurements, the value of the initial and final point fields are compared with previously obtained values, and scan data corrections are made to compensate for this difference, if any (the so-called linear regression procedure). The other option involves the use of zero-field chambers at the start and end position of the measurements and to correct the offset, if necessary, for every scan. This option requires more time and travel distance for the measurements and is used on special occasions only.

Three preparatory steps are executed prior to each measurement, but there is another important step that typically is performed only once or twice a year: absolute calibration of the Hall probe in the calibration magnet. The procedure is described in detail in the calibration magnet manual. The result of the calibration is the data file that is used to convert the Hall probe voltage signal to absolute values of measured magnetic field. It is important to point out that the Hall probe is the only sensor at the APS MMF that measures absolute values of magnetic field.

After all preparation steps are completed, the Hall probe system is ready for the measurements scan. A typical Hall probe scan for a 2.5-m-long ID takes about 20 sec. An example of the Hall probe Z-scan of an ID vertical field is shown in Fig. 7.

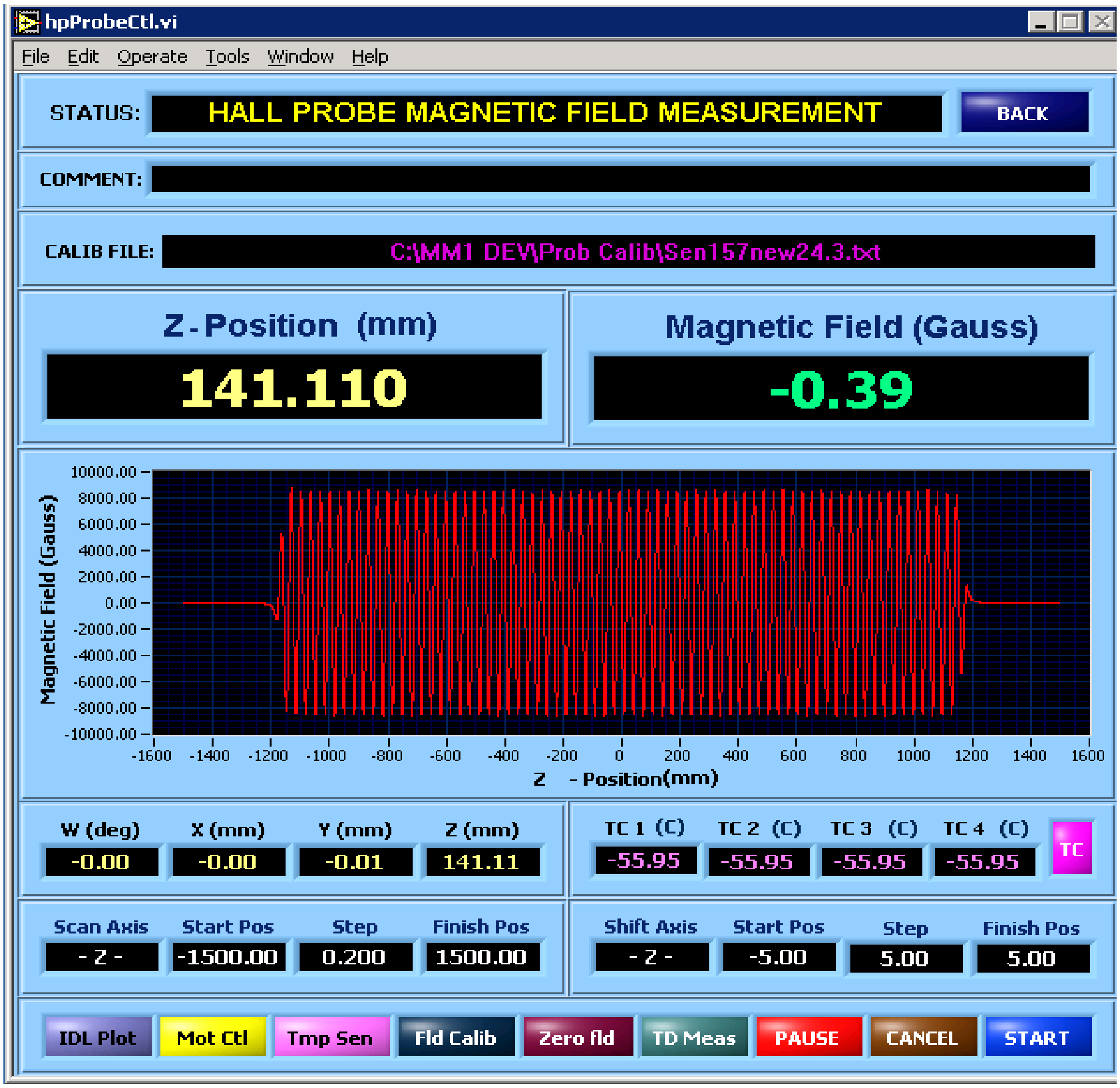

Fig. 7. Scan in the Z direction. The name of the calibration file used to convert voltage to magnetic field for this scan is shown at the top of the window.

Since the performance of the APS facility as a 3rd -generation x-ray source strongly depends on the performance of its IDs, it is critical to ensure the quality of data obtained during magnetic measurements and tuning of IDs. There are several ways to test the quality of Hall probe measurements. One of most commonly used at the APS is to examine the difference between two consequent scans. The less the difference, the better is the quality of the scan. An example of such a test is shown in Fig. 8. The rms of the field difference for two scans performed at a speed of 75 mm/sec and for the peak field of 0.8T is only ~1 G. A detailed view of the difference of these two scans is shown in Fig. 9. Clearly indication that different parts of the scan contribute differently to the errors, and the main contribution comes from the area near to the zero-field crossing points, where the slope is the highest. These errors are most likely associated with the probe's mechanical jitter and/or reproducibility of the probe positioning (~1-2 μm).

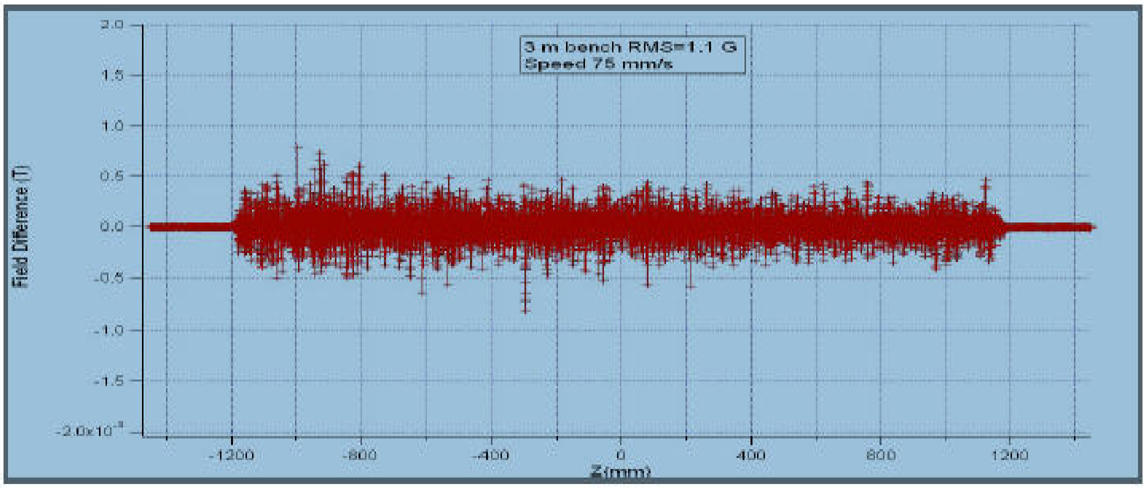

Fig. 8. Difference between two scans of the 3.3-cm-period Undulator A; rms error is 1.1 G.

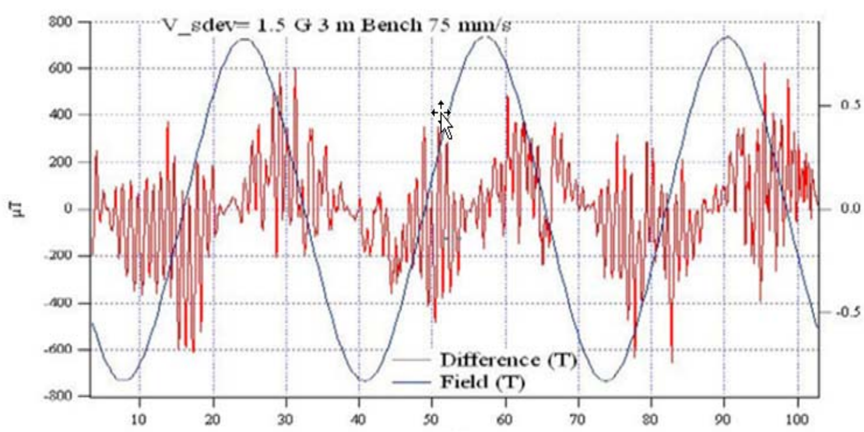

Fig. 9 Close view of the differential data. Left scale is for the main field, right scale is for the difference.

The differential set of data does expose and help to eliminate some sources of errors but not all of them. In addition to the differential data from the same sensor, it is good practice to obtain data from a different type of sensor and compare them. For measurements of field integrals, such crossreference is done between data from the Hall probe and that from a long rotating coil. For the average trajectory, data from the Hall probe and that from moving short or mini-coils are compared.

Sources of systematic errors that could affect the Hall probe measurements should be also understood and their influence should be taken into account. One such source of errors comes from the limit of the accuracy currently achievable for measurements of a low, near to zero, magnetic field. For the Sentron Hall probe, this value amounts to ~0.1 G.* Typically this limit doesn't affect the measurements and tuning of APS IDs. But for the LCLS undulator the uncertainty that just ~0.1 G would create for an average dipole field would "bump" the average trajectory beyond the specified 2 μm. In this case the long rotating coil provides a necessary reference for highly accurate field integral measurements. The detailed procedure for such measurements will be described in the next section.

Another source of systematic errors is the planar Hall effect. As was described above, the special procedure of compensation of the PHE has been implemented with the axial Arepoc Hall probe (see Fig. 5). The data obtained using such procedure are shown in Figs. 10 and 11. They demonstrate that the axial Arepoc Hall probe delivers very reliable measurements of the horizontal field in the presence of a strong vertical field, and the results are much less sensitive to vertical positioning compared with the Sentron Hall probe.

---

* There is an intent of the Hall probe designers and manufacturers to bring this value down to less than 0.01G [11].

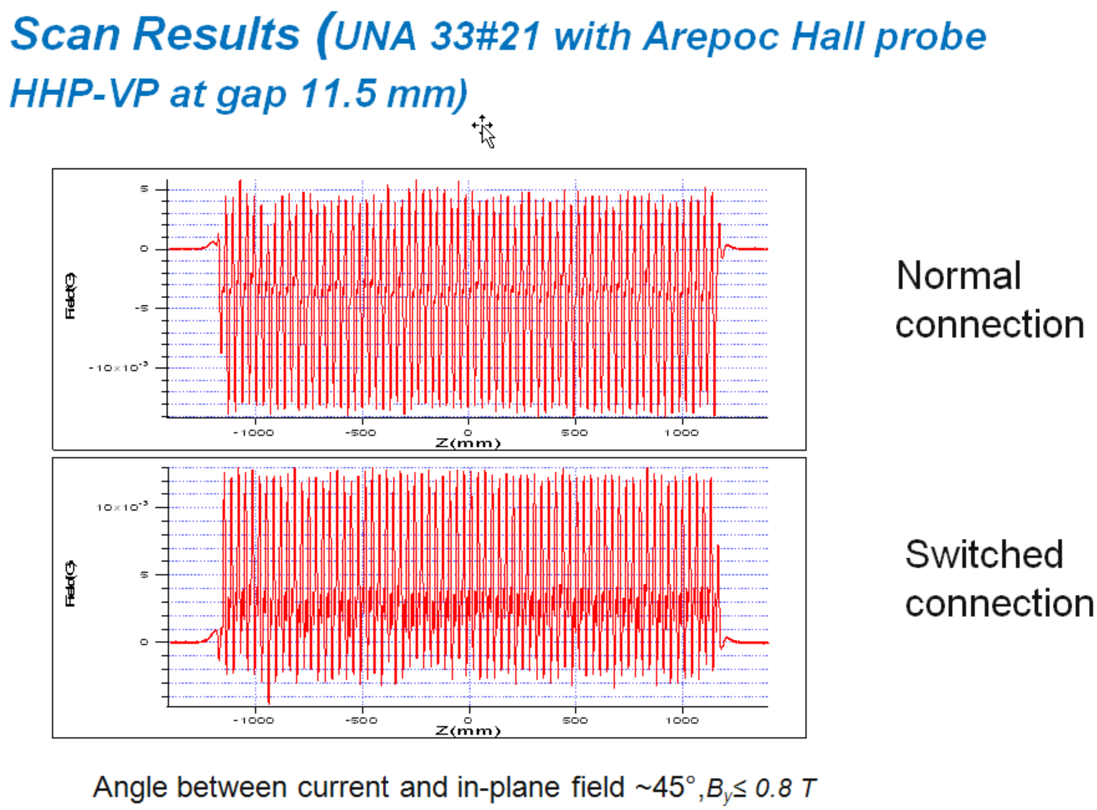

Fig. 10. Scan results of two consecutive scans.

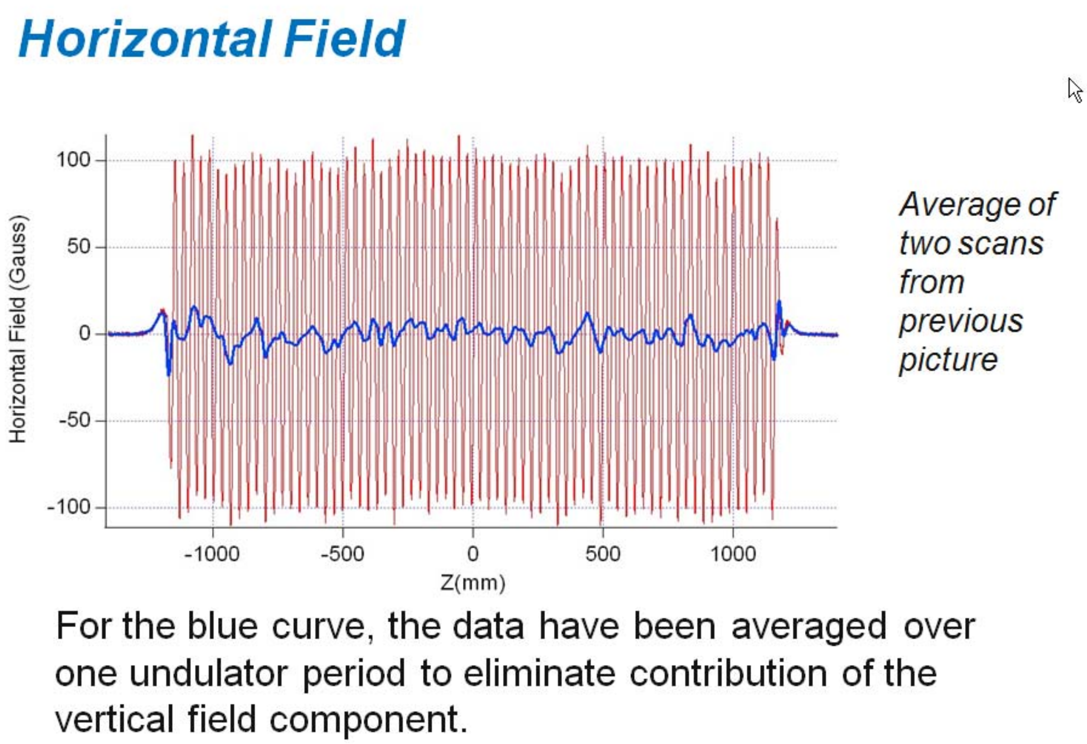

Fig. 11. Averaged data from two consecutive scans.

Short Moving Coils

Short moving coils are complimentary and sometime alternative to the Hall probe magnetic sensors used for the measurements of ID field integrals and average trajectories. Originally their development was mostly driven by the need for accurate measurements of the horizontal field integrals in the presence of a strong vertical magnetic field. But they are also useful for cross checking trajectory and field integral measurements performed by the Hall probe.

There are two types of short moving coils at the APS. Both of them are multiturn coils that could be placed on the same stand with a goniometer as the Hall probe. One type is about 90 mm long, several hundred turns, and it collects the signal from approximately 2-3 periods of an APS Undulator A (Fig. 12).

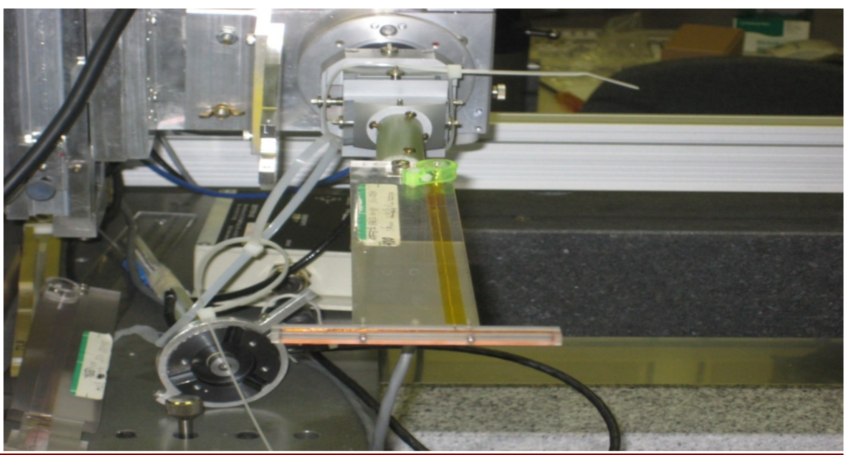

Fig. 12. Short moving coil at 6 m bench. Parameters: 420 turns, 1250 cm^2*turns, L=81 mm, W*D=1.5*3.5 mm^2

Another coil is much shorter, just a few millimeters, and is called a minicoil; it has several thousands turns (Fig. 13A&B).

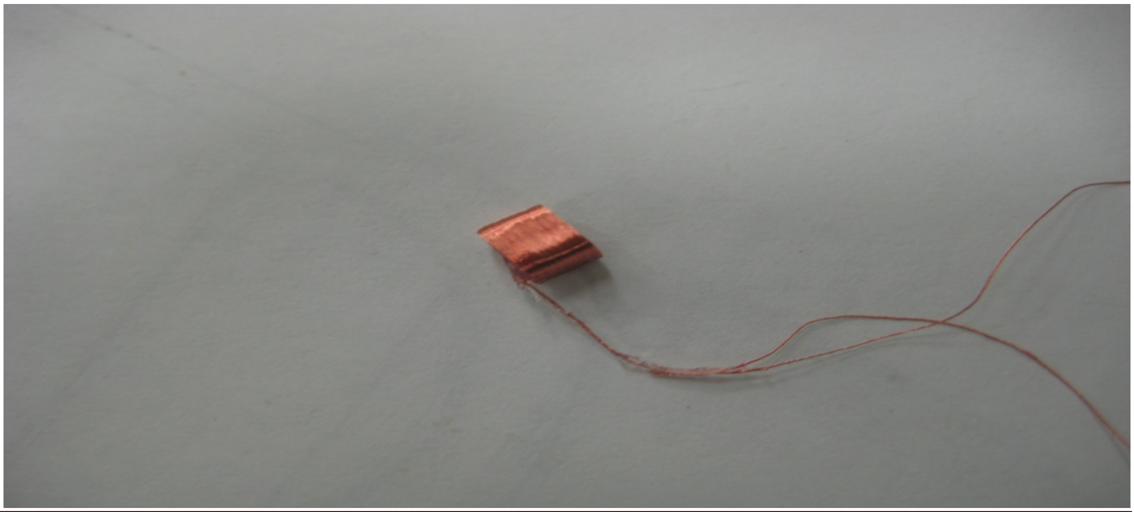

Fig. 13A Minicoil: 5.9 x 4.0 x 3.9 (mm^3); 5000 turns; 22 μm copper wire, 608 area-turns

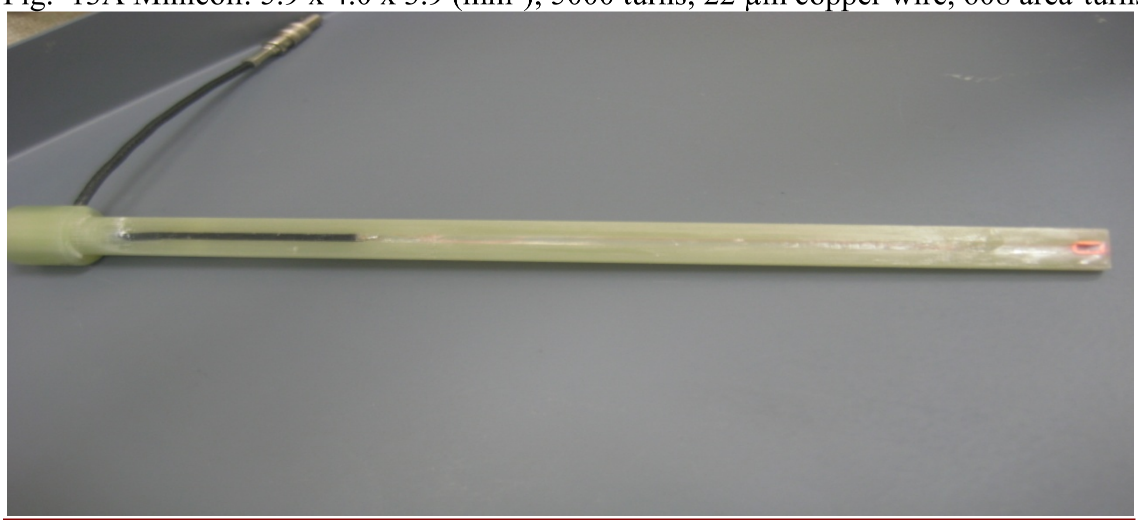

Fig. 13B. Minicoil assembly for vertical field measurements.

Each type of these coils can be used for measurements of vertical and horizontal magnetic fields in IDs. Although stages and motion control systems are identical to that of the Hall probe, the signal readout electronics for moving coils is different. Fig. 2 shows that the remotely controlled Walker MF-10D fluxmeter is used to integrate the signal from the coil.

Both types of moving coils measure the same ID parameters as the Hall probe: the average trajectory and field integrals. But, unlike the Hall probe, which measures absolute values of the magnetic field and provides very detailed trajectory data, moving coils measure only the field flux difference and a less detailed trajectory. At the same time, the moving coils have several advantages: measured flux is proportional to the field, i.e., there are no nonlinear effects typical for the Hall probe and therefore the calibration type measurement is sufficient just for one point. Also, there is no temperature dependence. A typical accuracy of the field integral measurements with moving coils is about 2-5 G-cm.

Prior to the measurements, each coil has to be aligned with respect to the ID. The same linear and rotational stages as for the Hall probe are used, and coil alignment is usually controlled and verified using optical instruments. For the short moving coil, it is important to position its centerline exactly on the ID centerline due to the relatively large length of the coil. Alignment of the minicoil has to follow the same steps as for the Hall probe.

Since both coils don't measure the absolute magnetic flux, it is important to calibrate them prior to the measurements. The calibration of the short moving coil is performed in the special dipole magnet. This magnet is not large, and the homogenous field area is smaller than that of the short moving coil. Therefore Hall probe measurements of the magnet first field integral are conducted first and are used as the calibrated reference for the coil. The example of such calibration is shown in Fig. 14. The calibration of the minicoil also can be done in the same dipole magnet, or sometimes even in the ID.

It is important to point out that, for both coils, the output signal reading has to be zeroed at the initial point of any measurement. After the measurement is completed, the linear regression procedure is applied to the measured data while using the Hall probe data for the same initial and final points as the reference.

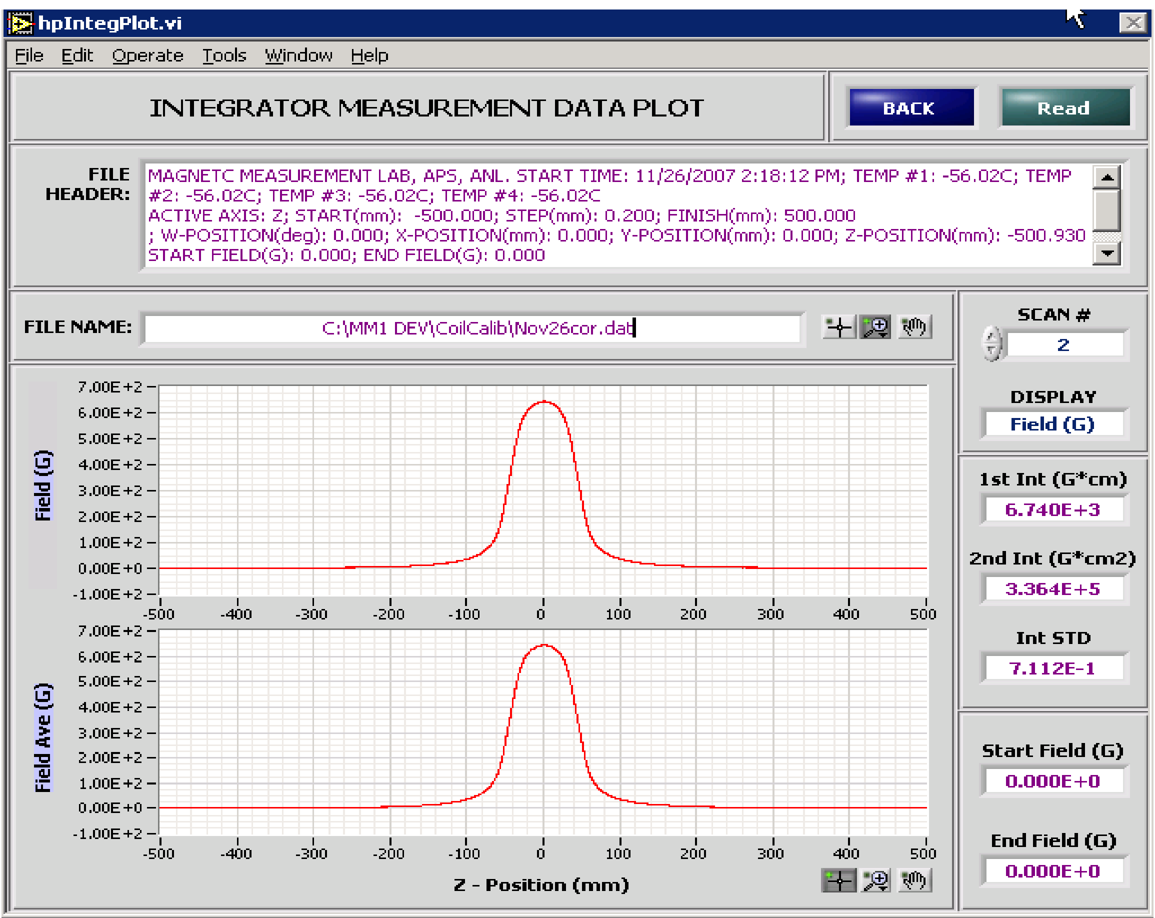

Fig. 14. Dipole magnet scans with the short moving coil. Second scan data are shown at the top, averaged of two scans data are at the bottom. Calculated data are at the right part of the screen.

As was already mentioned, the cross check of measurements of the same ID with two different types of sensors is quite useful for quality control. Measurement results of the same ID – an 8.5-cm wiggler – obtained with the Hall probe and minicoil, respectively, are presented in Fig. 15A&B, which shows that data obtained by different sensors in this case are in very good agreement.

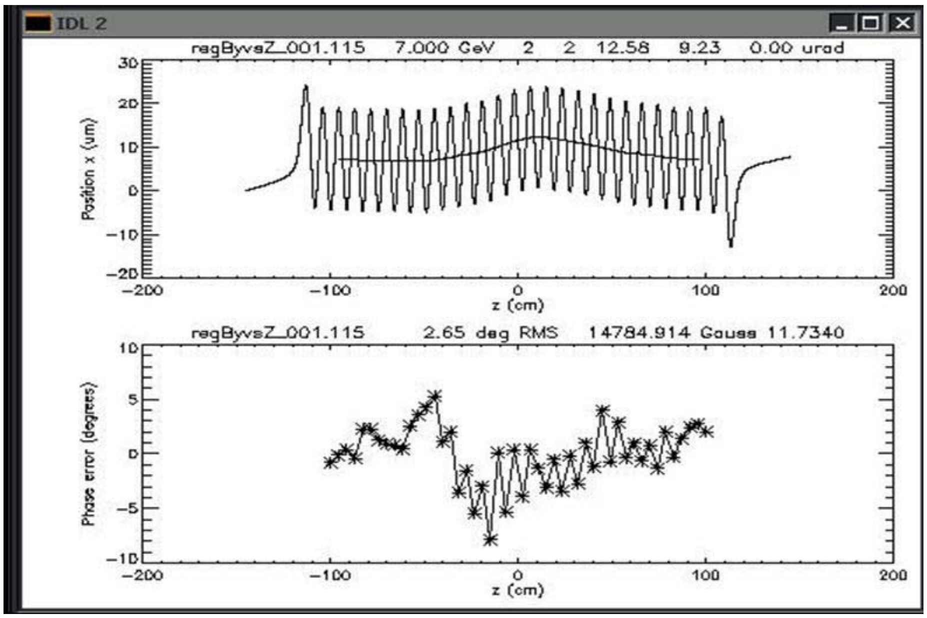

Fig. 15A. Hall probe measurements. Effective field B_{eff}=14785 Gauss, phase errors std=2.65°.

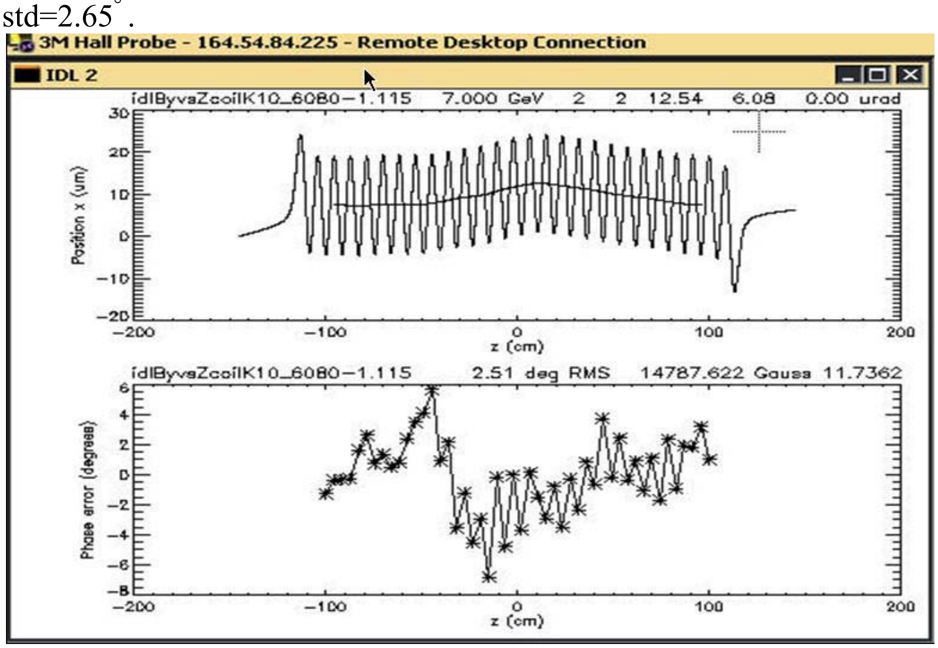

Fig. 15B. Minicoil measurements. Effective field B_{eff}=14788 Gauss, phase errors std=2.51°.

Long Stretched Rotating Coil

The long stretched rotating coil is used to measure, with the high accuracy, the first and second field integrals and their high moments [3]. It is important to emphasize that the measurement technique based on the long stretched rotating coil provides absolute values of measured field integrals. Therefore it is also used to cross check and validate the Hall probe measurement data for field integrals.

Since April 2010, single BeCu wire has been used at the APS MMF to make the long rotating coil. Several months of operation with new coil proved to be very successful. The performance of this coil by far exceeds the performance of long stretched coils previously used at the APS MMF.

The 0.1-mm-thick BeCu single wire is coiled around small-diameter cylinders that are part of support system placed at a distance of several meters along the Z axis. The wire forms the rectangular loop/coil with the 3.5-mm width. Each cylinder is attached to manually adjustable X-Y coordinate slides, and the slides themselves are placed on motorized, rotating Z-axis stages. Finally, these stages are placed on the coil support system that consists of another set of X-Y-Z motorized slides (see Fig. 16). This elaborate mechanical system permits: a) accurate alignment of the coil inside the ID gap in all directions, b) control and adjustment of the tension applied to the wire, and c) alignment of the Z-midline of the coil with the axis of rotation. The rotating motorized stage and X stage at one end of the bench are equipped with encoders. We have the ability to position the coil with 1 μm accuracy along the X axis, and accurately, with 0.005° to control the rotation. Since the stretched BeCu coil has less than 100 μm sag, its contribution to the total error of the measurements is negligible.

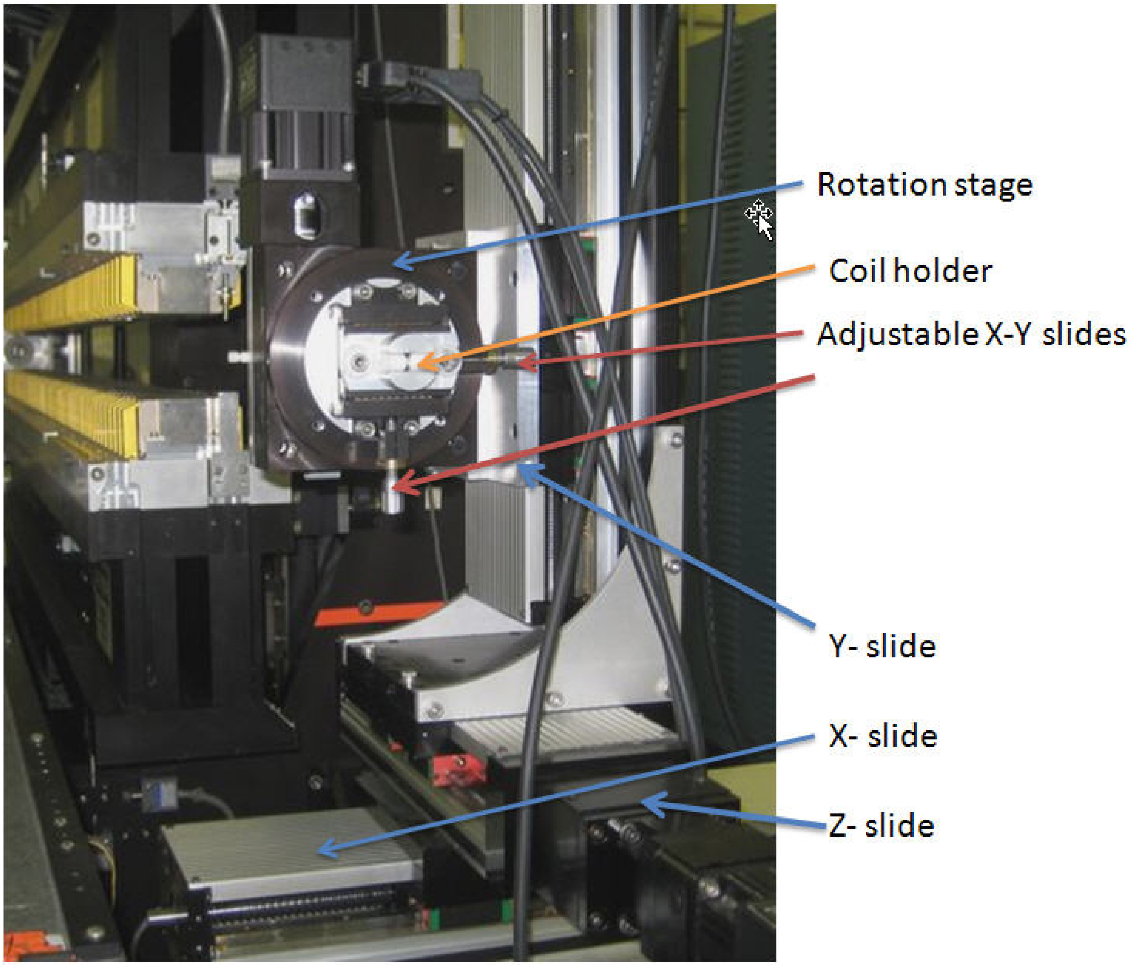

Fig. 16. Coil stages at the upstream end of the 3-m bench.

There are two modes of the coil operation. 1.*Translation mode:* the coil is moved parallel to itself with the coil's plane positioned vertically for measurements of the first horizontal field integral as a function of the translation coordinate, or horizontally for measurements of the first vertical field first integral as a function of the coordinate; these measurements provide only relative values of measured field integrals, but deliver its high moments values. 2. *Rotating mode*: the coil is rotated by 360°; this measurement provides the absolute value of the first field integral. There is also a special option for measurement when one end of the coil is rotated by 180° and, with the cross in the center, the coil forms the figure 8. In this configuration, the measured data are the function of both the first and second field integrals. By getting values of the first field integral from the rotating mode measurements, one can calculate the second field integral [11].

Accurate control of the rotation permits one to fit the measured data with the real sin wave function, and, as a result, errors associated with wire vibration are practically eliminated. It results in a total rms error for the measurements of the first field integral of less than 0.5 G-cm. Therefore only two measurements for every data point, just to confirm the reproducibility, are required.

The single BeCu wire coil is a very accurate and reliable magnetic sensor that proved to be the necessary and useful tool to characterize APS IDs.

An example of measurements results obtained with the long stretched coil is shown in Fig. 17.

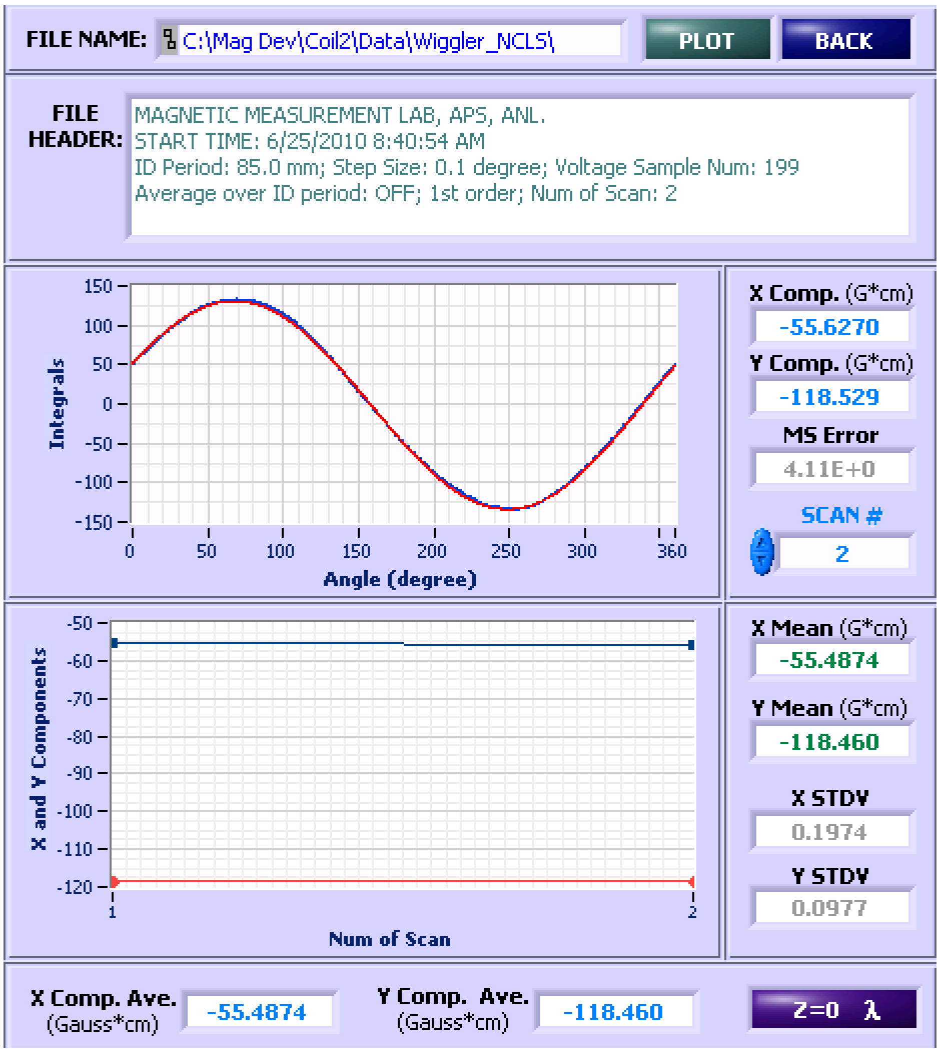

Fig. 17. Earth field magnetic measurements using the long rotating coil; rms error is <0.5 G-cm.

Stretched wire

Another quite useful and complimentary sensor to the rotating coil and the Hall probe is a stretched wire. The stretched wire is a single loop that consists of the stretched portion placed inside the ID gap and extending outside of the gap by about 50 cm, and another portion that hangs freely outside ID and closes the loop. Alignment of the stretched wire is performed by sliding the stretched wire along the Z portion of the loop towards the X=0 and Y=0 location. The alignment process is controlled and verified by optical instruments.

The measurements of the first field integral are performed by moving the stretched portion of the loop parallel to itself and recording the signal resulting from the magnetic flux change. Geometrical imperfections of the wire are not important in this case, because the wire is moving parallel to itself. In order to measure the second field integral, only one side of the stretched portion is moved. For both measurements, the area covered by the loop is much larger than that for the rotating coil. It results in noticeably larger noise, but, due to the small step and large number of measured points, the final results are reliable enough, especially for first and second field integrals. It is important to point out the unique advantage of the stretched wire technique: the ability to measure the second field integral only. As was described in the previous section, the stretched rotating coil in the figure 8 rotation mode measures both first and second integrals but doesn't separate them. The stretched wire measurements, when the upstream end of the wire moves while the downstream end of the wire is fixed, provide data just for the second field integral. This can be easily shown using the equations from Ref. [12] applied to the case of wires with a delta shape.

One example of the stretched wire measurements is shown in Fig. 18.

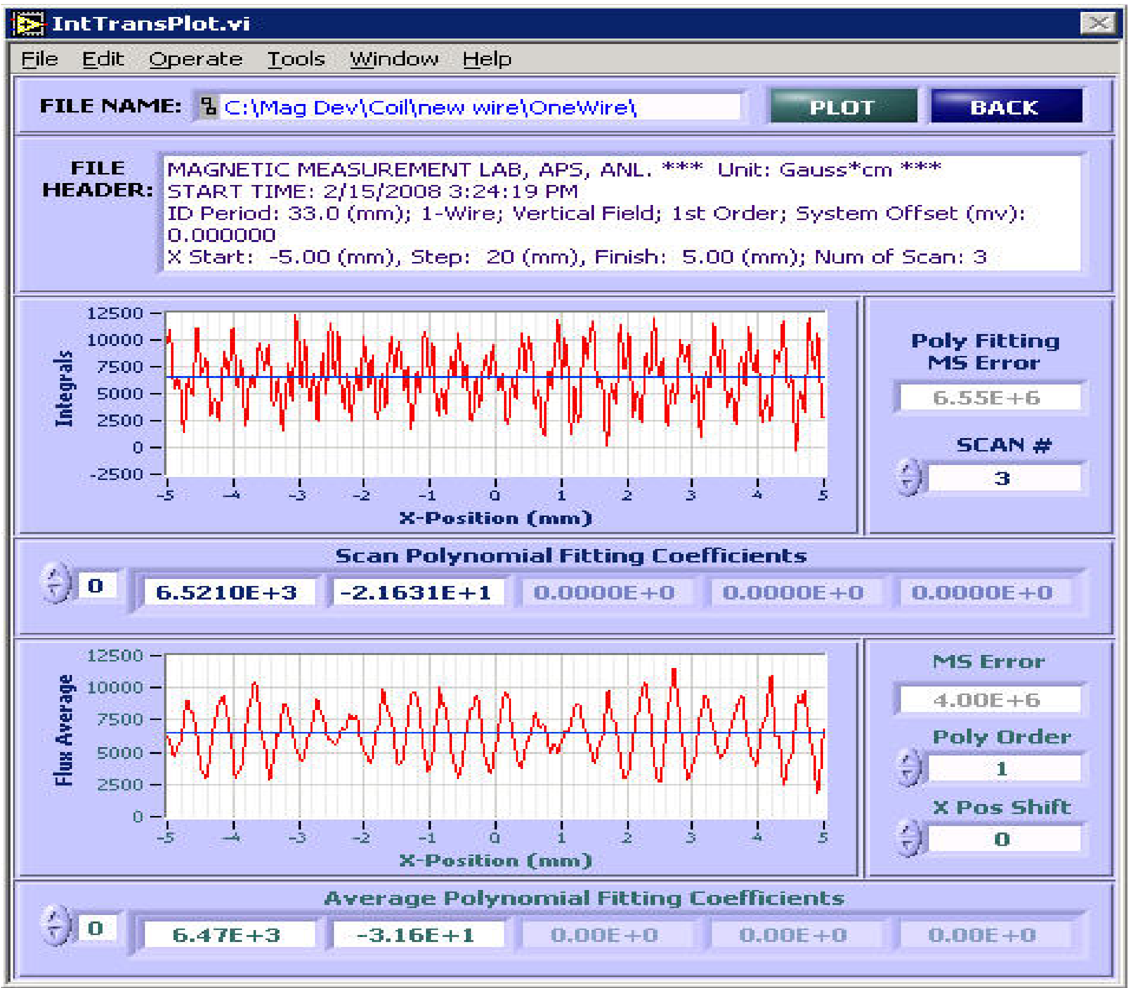

Fig. 18. Stretched wire measurements of the dipole field.

References

1. R. Dejus, I. Vasserman, S. Sasaki, L. Moog, "Undulator A magnetic properties and Spectral Performance," ANL/APS/TB-45, May 2002.
2. L. Burkel, R. Dejus, J. Mains, J. O'Brien, J. Pfluger and I. Vasserman,"The Insertion Device Magnetic Measurement Facility: Prototype and Operational Procedures," ANL/APS/TB-12 March 1993.
3. Joseph Z. Xu and Isaac Vasserman, "A New Magnetic Field Integral Measurement System," Advanced Photon Source, Argonne National Laboratory, Argonne, IL 60439 USA , Proceedings of the 2005 Particle Accelerator Conference, IEEE (2005), 1808, *http://accelconf.web.cern.ch/AccelConf/p05/PAPERS/MPPT023.PDF*
4. Hall Probe Calibration System Users Guide-1.pdf, \\oxygen\iddata\manuals;

5. B.N.Deriy, O.A.Makarov, I.B.Vasserman, “The Helmholtz Coils Measurement System,” 7th International Computational Accelerator Physics Conference, Michigan State University, Lansing October 15-18, 2002.
6. Joseph Z. Xu and Isaac Vasserman “A New Magnetic Field Integral Measurement System,” ANL/APS/TB-49, March 2005.
7. I. Vasserman, J. Xu, “Upgraded Accuracy and Reliability of Insertion Device Magnetic Measurements at the Advanced Photon Source,” IMMW-14, September 26-29, 2005, Geneva, Switzerland.
8. R.S. Popovic, Hall Effect Devices, second edition, IoP, Institute of Physics Publishing, ISBN 0 7503 0855 9.
9. I.B. Vasserman ,” Test Of Horizontal Magnetic Field Measurements In The Presence Of A Strong Vertical Field,” Proceedings of the 2004 FEL Conference and 11th Annual FEL User Workshop, Trieste, Italy, 9 Aug -3 Sep 2004, 527-529.
10. I. Vasserman, J. Xu, “Cancellation of the Planar Hall Effect Voltage by Interchanging Connections on a Hall Sensor”, IMMW-16, Bad-Zurzach, Switzerland, October, 26-29, 2009
11. D. R. Popovic Renella, R. S. Popovic, “Hall magnetic transducers with NMR-like resolution,” IMMW-16, Bad-Zurzach, Switzerland, October, 26-29, 2009.
12. D. Frachon, P.M. Ivanov, E.A. Medvedko, L. Turner. I. Vasserman (APS), V. Popic, N. Vinokurov, P. Vobly (BINP), “Magnetic moments and Field Integrals Compensation of the Elliptical Multipole Wiggler,” IMMW-9, CEA/Saclay, June 19-22, 1995; D.Frachon, I.Vasserman, et.al.,ANL/APS TB-22, 1995.